Progress on the Frequency Stabilization of MW-Class 140 GHz Gyrotrons at W7-X with a Phase-Locked Loop

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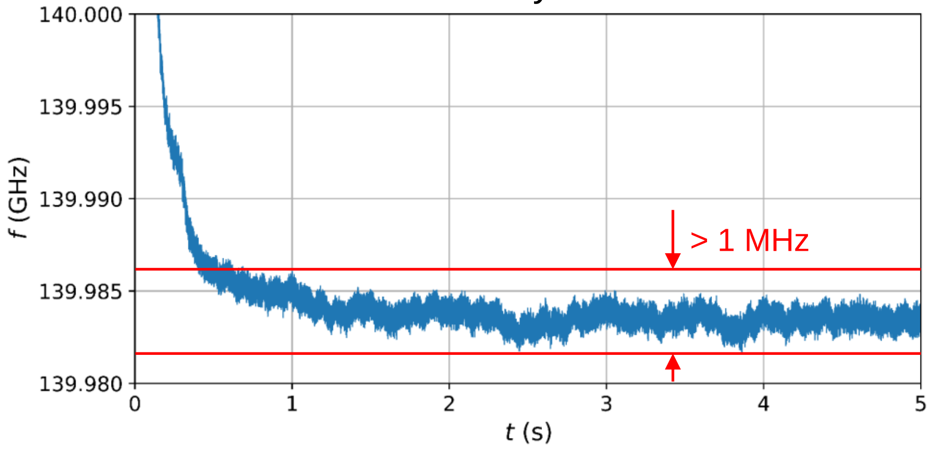
Introduction (1/2)

- Until now: gyrotrons are free running oscillators
- Unwanted frequency variations from
  - Cavity temperature (expansion)
  - Power supply noise
  - Vacuum conditions
- Applications of frequency stabilized high-power gyrotrons:
  - Collective Thomson Scattering (CTS) diagnostic
  - Fast Directional Switch (FaDiS) for high-power millimeter-wave beams
  - Direct ion heating at the ion cyclotron resonance frequency with beat waves at the electron cyclotron frequency

Free-Running Frequency of Megawatt-Class W7-X Gyrotron

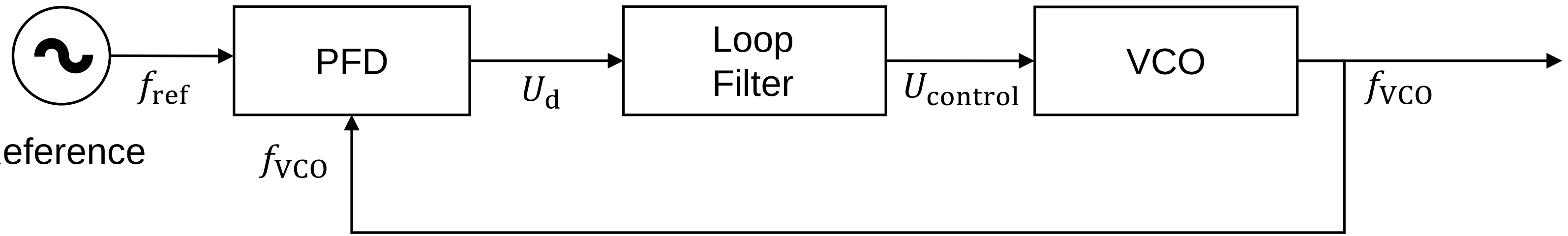


Introduction (2/2)

- Two methods to frequency stabilize a gyrotron:
  - Injection locking
  - External control circuit
- No need to change the gyrotron design with an external control circuit
- Phase-Locked Loop (PLL) is a well known method for phase and frequency stabilization of free-running oscillators
- Demonstration of PLL stabilization (gyrotrons with triode-type MIG)
  - 100 W, 263 GHz gyrotron: line width as narrow as 1 Hz [1]
  - 25 kW, 170 GHz gyrotron: line width as narrow as 1.5 Hz [2]

[1] A. Fokin *et al*, *Scientific Reports* **8**, 4317 (2018)
[2] G.G. Denisov *et al*, *22nd IVEC 2021* (27-30 April 2021)

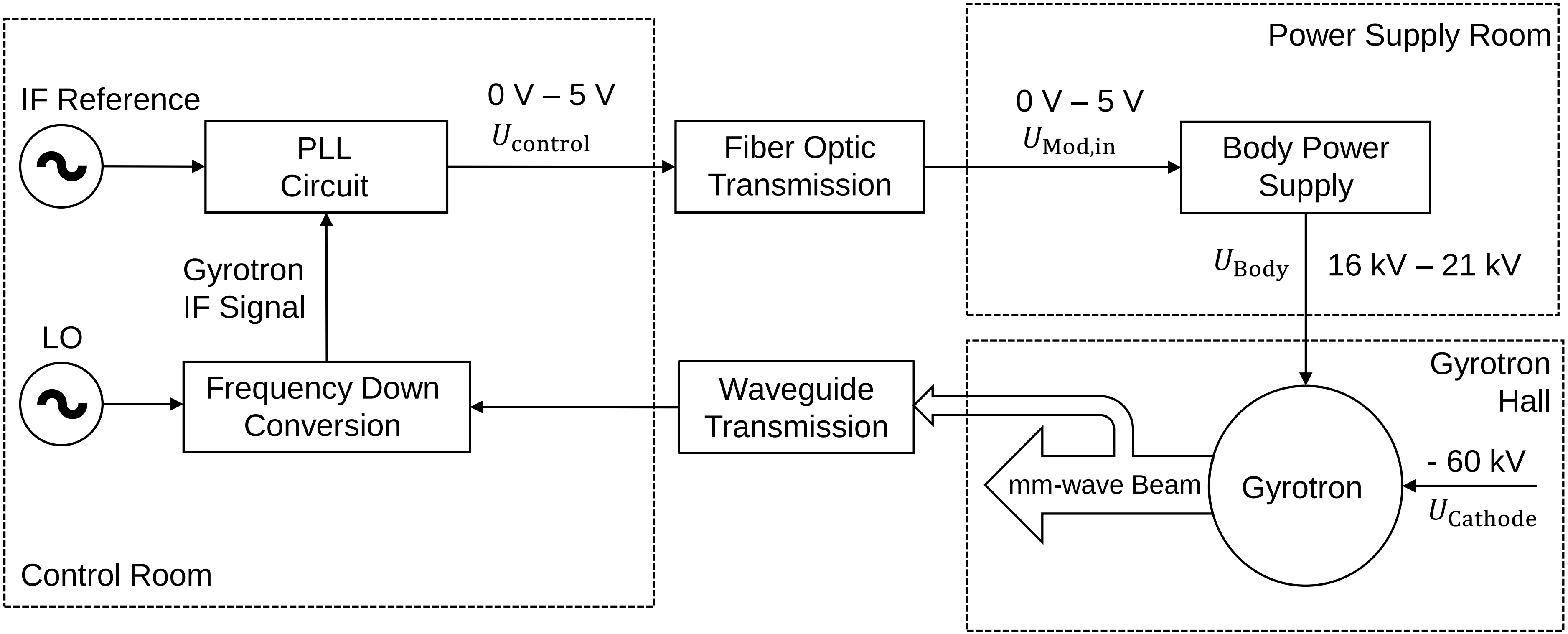
PLL Block Diagram



- **Phase Frequency Detector (PFD):** compares the phase and frequency of two signals and develops an output signal U_{d}, which is proportional to the phase or frequency error
- **Loop Filter:** filters appropriately the output signal of the PFD for the VCO and determines the dynamics and stability of the control loop
- **Voltage Controlled Oscillator (VCO):** generates an output signal with a frequency depending on the input voltage

$$f_{\mathrm{VCO}} = f_0 + K_{\mathrm{VCO}} U_{\mathrm{control}}$$

Experimental Setup (Diode-Type MIG)



Gyrotron Experimental Parameters

- Experiments with W7-X ECRH gyrotron from manufacturer CPI

- Gyrotron Parameters:
  - U_{cathode} = - 60 kV
  - U_{body} = 16 kV – 21 kV
  - I_{beam} = 38 A

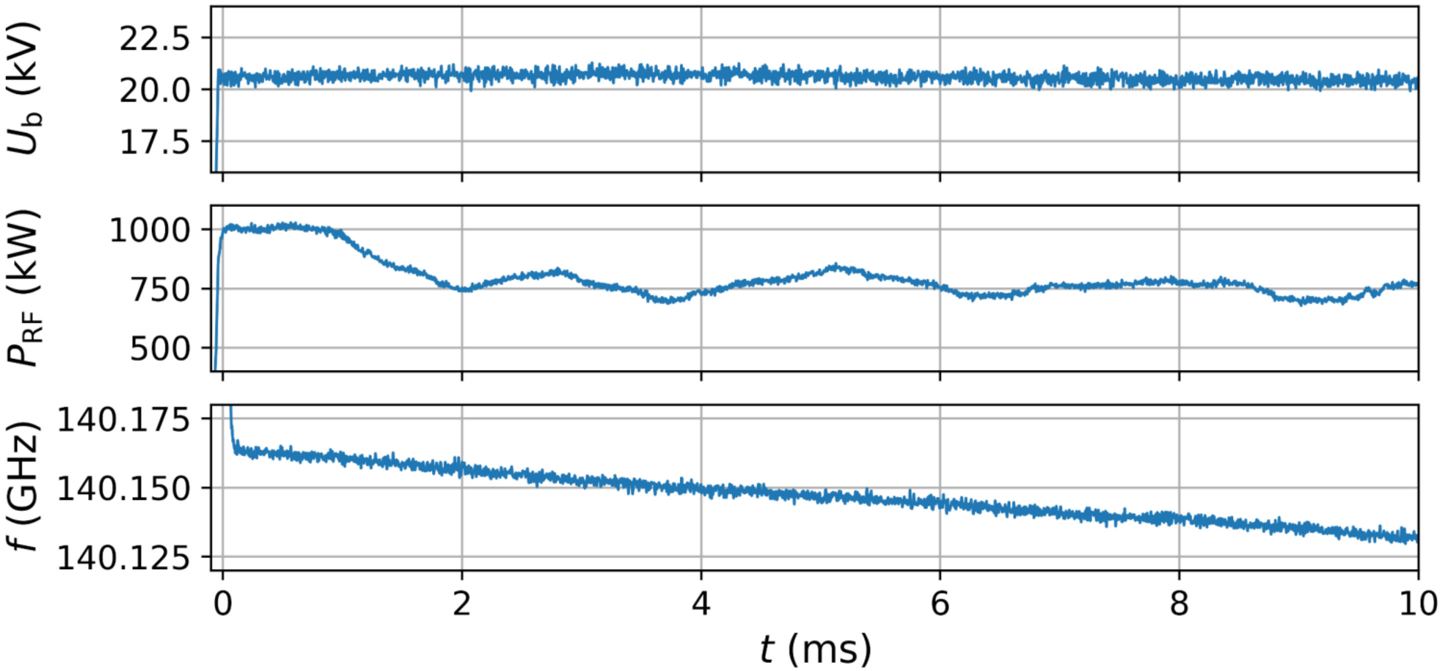
- Stabilization to an IF frequency of 45 MHz

- Short and long pulse shots

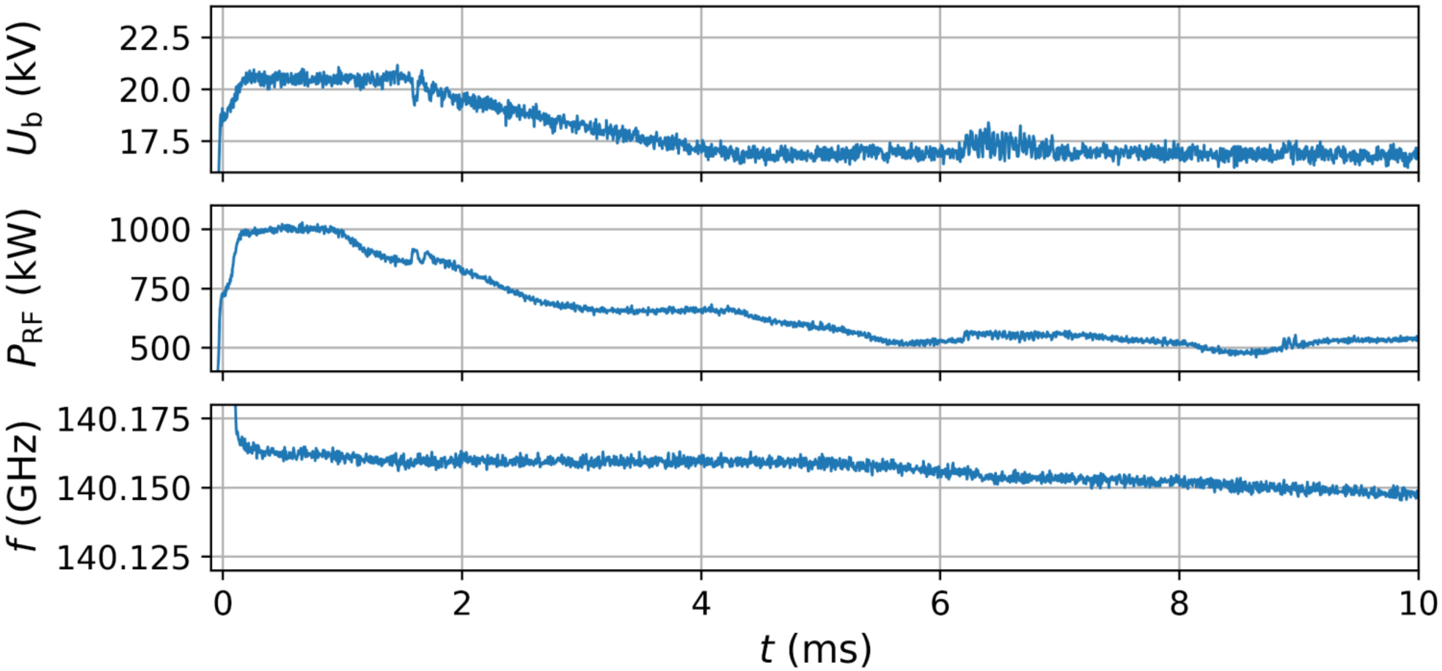
Short Pulse Experiments

- Collective Thomson Scattering diagnostic at W7-X requires short pulses in the 2-5 ms range
- **Problem:**
  Frequency drop at the beginning due to electron beam neutralization and cavity expansion from heating
- Counter frequency drop with large change in body voltage

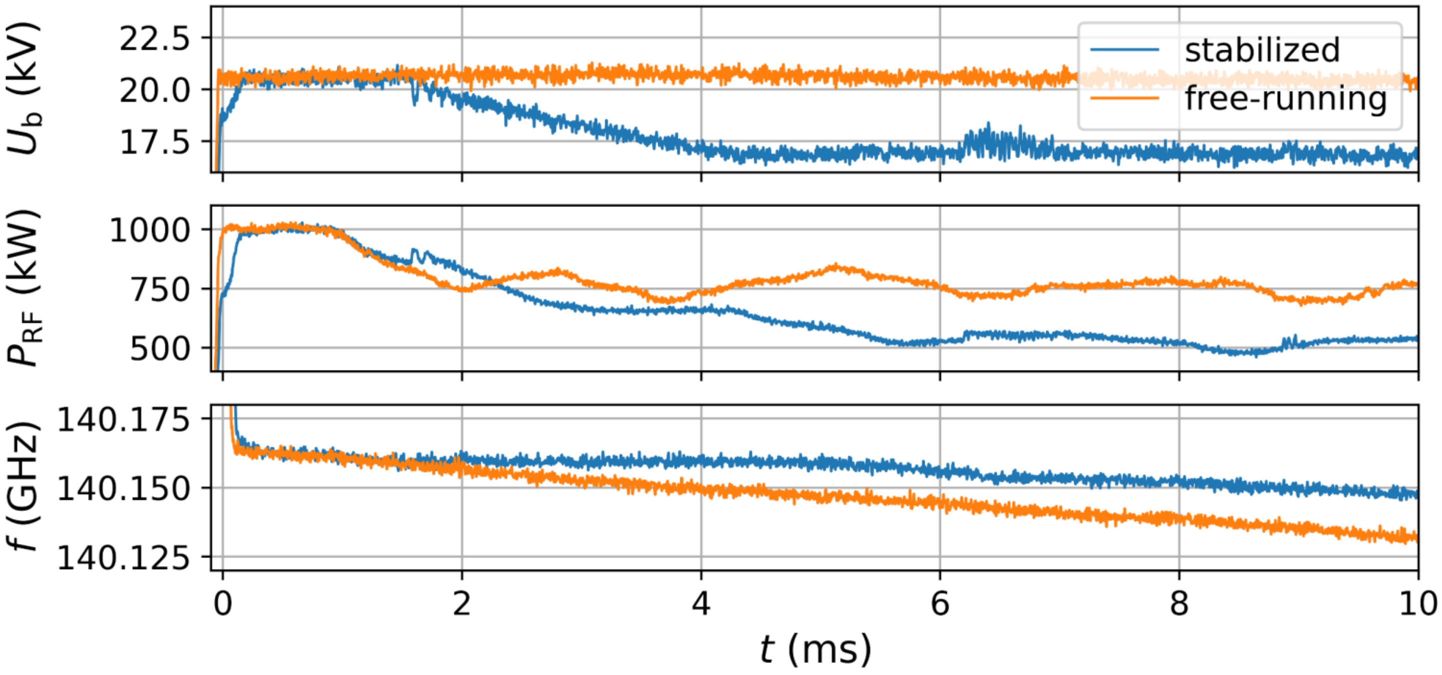
10 ms Short Pulse Free-Running



10 ms Short Pulse Stabilization to 140.160 GHz



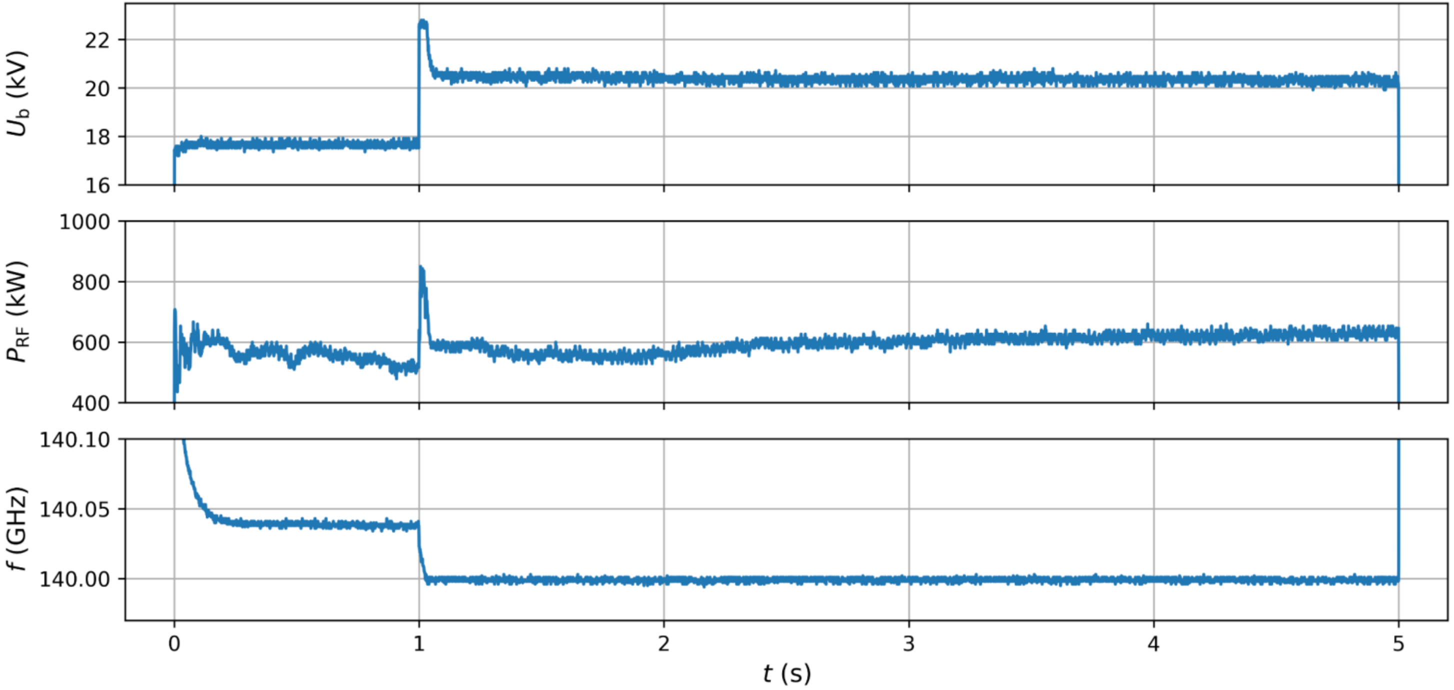
10 ms Comparison Free-Running - Stabilized



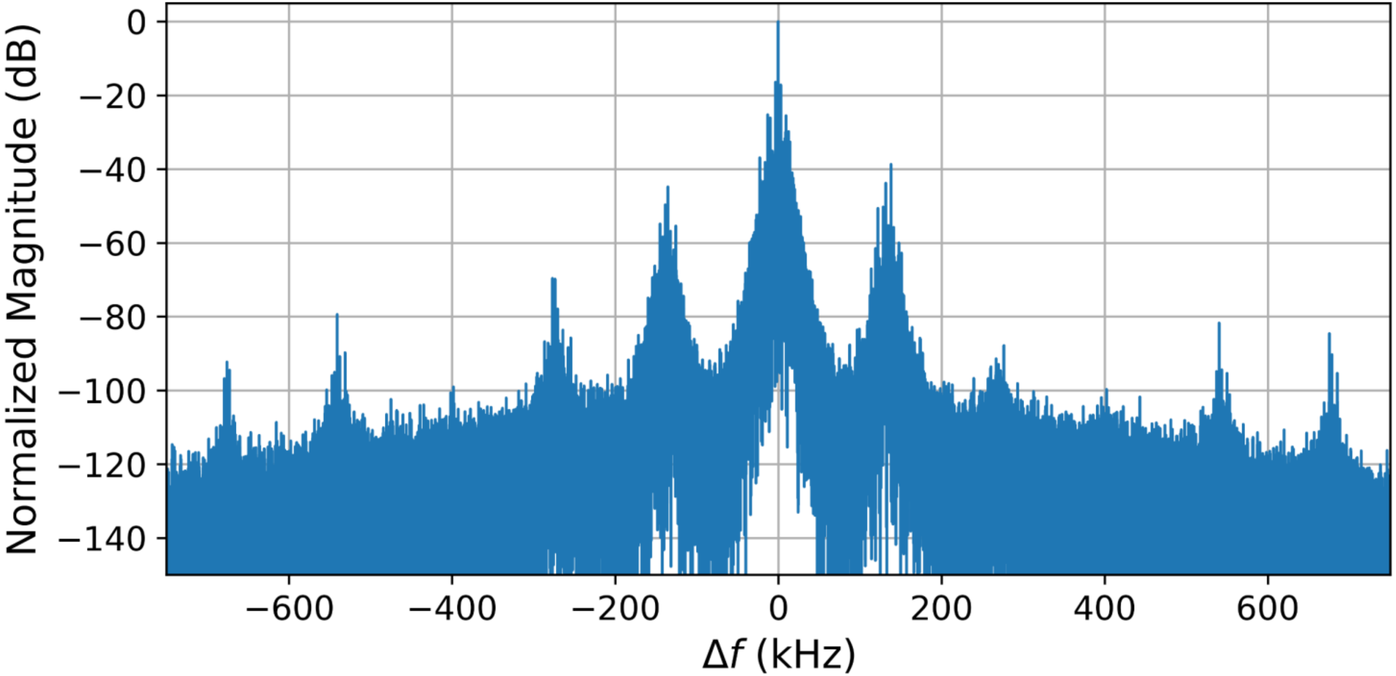
Long Pulse Experiments

- Frequency stabilization after initial frequency drop
- Free-running frequency only changes in the MHz range
  ➡ Small corrections in body voltage required to stabilize the frequency (below 1 kV)
- Control circuit enabled after 1 s from the start of the pulse
- Frequency is kept stable until the end of the pulse

Frequency Stabilized Gyrotron at 140.000 GHz

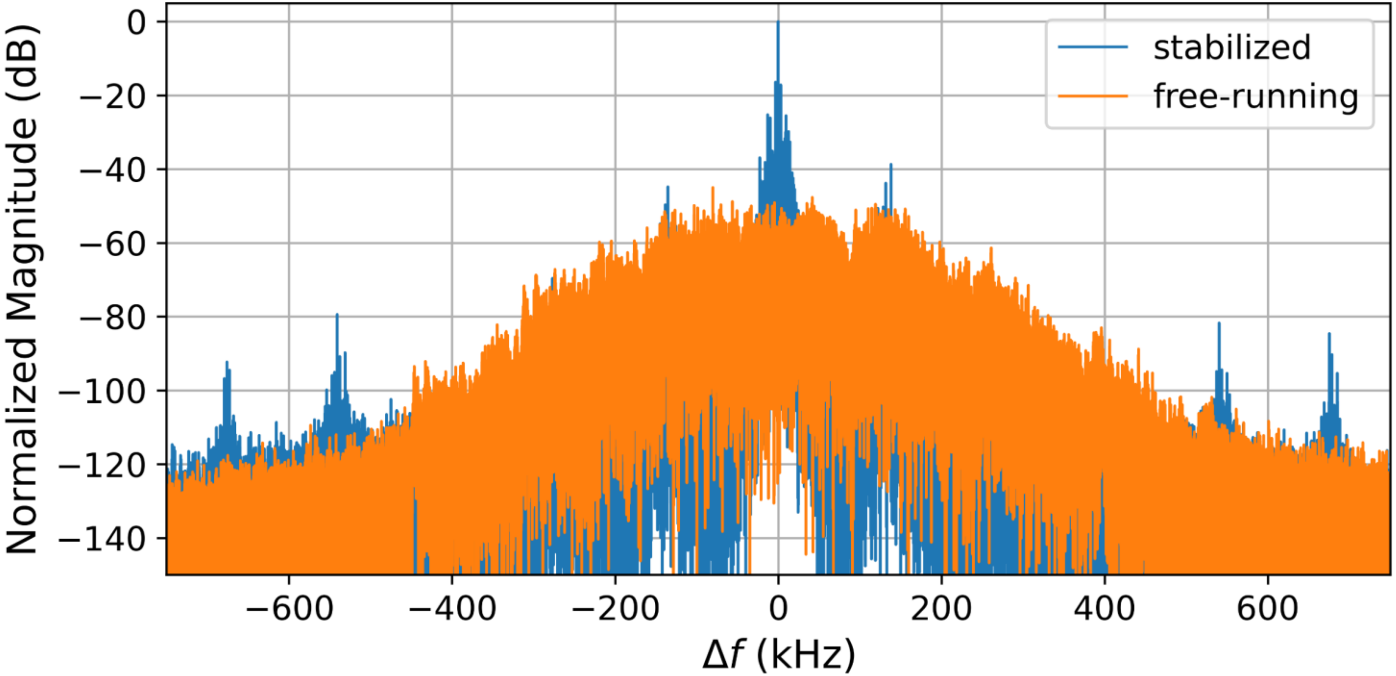


Frequency Stabilized Gyrotron at 140.000 GHz



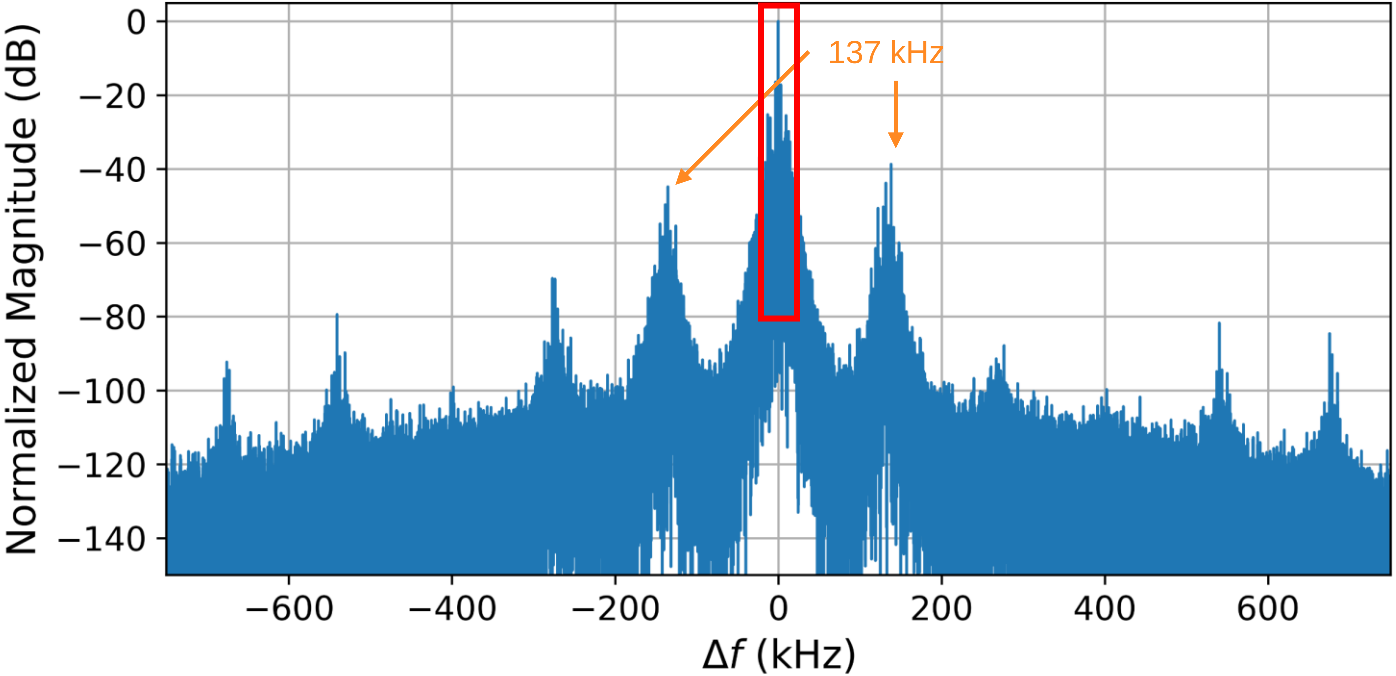
f = 140.000 GHz + Δf

Comparison Free-Running and Stabilized Spectrum



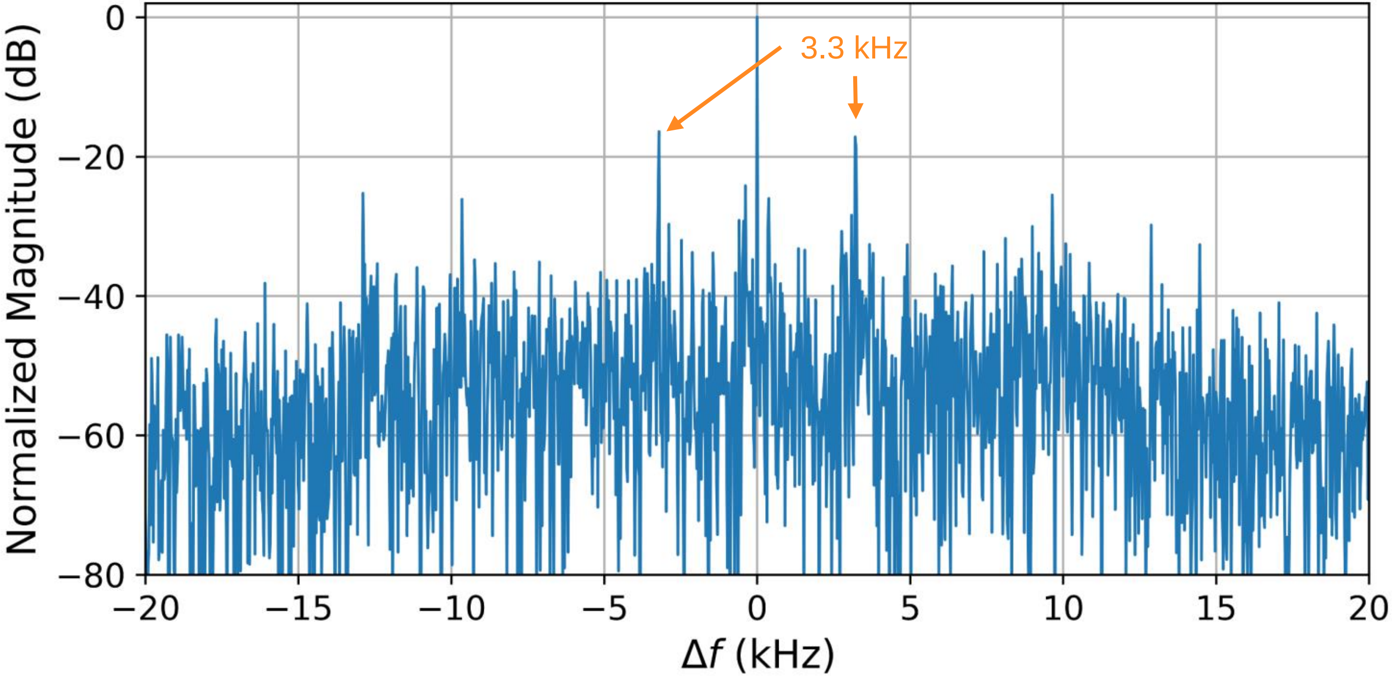
$f = 140.000\ \text{GHz} + \Delta f$

Frequency Stabilized Gyrotron at 140.000 GHz



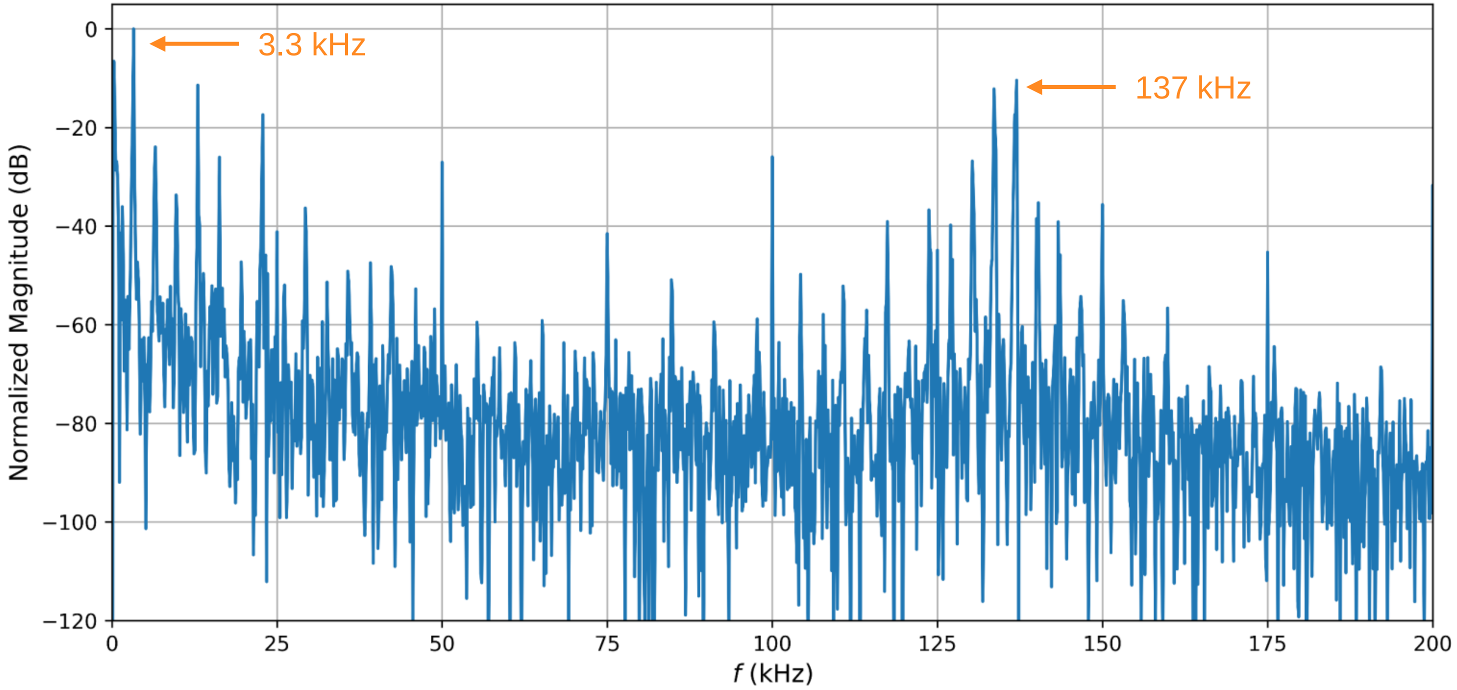
f = 140.000 GHz + Δf

Frequency Stabilized Gyrotron at 140.000 GHz (Zoomed In)



f = 140.000 GHz + Δf

Noise Spectrum of Cathode Power Supply



Conclusion and Outlook

- Experiments show the potential to stabilize the frequency of a high power gyrotron with diode-type MIG and single-stage depressed collector via the body voltage
  - Possibility to set a desired frequency
  - Full -20 dB bandwidth of < 20 kHz

- Investigation of side-bands in the stabilized spectrum, which are coming from the power supplies (3.3 kHz and 137 kHz lines)

- Implementation of PLL circuit at W7-X gyrotron for
  - Collective Thomson Scattering diagnostic at 175 GHz
  - Experiments to explore the possibility of direct ion heating at the ion cyclotron resonance frequency with beat waves at the electron cyclotron frequency